THE USE OF THE MOTOR AS A TRANSDUCER TO MONITOR SYSTEM CONDITIONS

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Abstract: Motor current and power analysis methods have been developed to assist in the condition monitoring of a variety of motor-driven devices. The early work in this area was conducted at Oak Ridge National Laboratory (ORNL) on motor-operated valves in the mid-to-late 1980's in support of the U.S. Nuclear Regulatory Commission's Nuclear Plant Aging Research Program. The successful implementation of motor current signature analysis (MCSA) as a diagnostic for valves led to its application to other devices and to refinements in the methodologies used.

In the last few years, work for the Nuclear Regulatory Commission and independent activities at ORNL and the Y-12 defense plant have resulted in additional, more thorough consideration of the merits of using motors as transducers for understanding system conditions. A variety of applications, ranging from fractional to over 1200 horsepower have been analyzed.

Motor current and power analysis have been found to provide information that is complementary to that available from conventional diagnostics, such as vibration and pressure pulsation analysis. Inherent signal filtering associated with rotor to stator magnetic field coupling does limit the high frequency response capability of the motor as a transducer; as a result, certain phenomena, such as pump or fan vane pass energy, is not readily apparent in the motor electrical signals. On the other hand, the motor-monitored parameters have often been found to be much more sensitive than vibration transducers in detecting the effects of unsteady process conditions resulting from both system and process specific sources.

Key Words: Condition analysis; current; MCSA; motor; power; process conditions; system analysis.

Background: Almost all motor-driven devices experience fluctuating loads. The types of load fluctuations are dependent upon the specific design features of the device and the system within which it is operated. The load fluctuations can be periodic or chaotic in nature. For those loads which are periodic, the period can vary from fractions of milliseconds to months or years.

The relatively straightforward recognition that the motor speed (for induction motors), current, power and power factor change in response to load changes led investigators studying potential means of diagnosing motor-operated valve conditions to evaluate the usefulness of the motor as a

transducer in the 1980's [1]. The ability to identify a variety of load-related phenomena, such as lubricant degradation and gear tooth wear, by use of demodulated motor current was demonstrated. The researchers dubbed the methodology of analyzing the time and frequency domain current signals to understand the driven device conditions <u>motor current signature analysis</u> (MCSA). The application of this term has since been applied rather broadly to a variety of waveform and spectral analysis techniques, and has been used when characterizing both the motor and the driven device.

Probably the most common use of current monitoring is by operators simply observing permanently installed ammeter readings to verify that the motor is energized and that its current draw is consistent with expectations. In a diagnostic sense, spectral analysis of the motor current has been used to help understand the condition of the motor, with primary focus on rotor eccentricity and rotor conductor condition.

While the use of motor current data is helpful in understanding motor electrical and magnetic field conditions, this paper is focused on understanding other conditions in the drive train. There are both some relatively straightforward as well as more complex applications of motor current or power data. This paper will not discuss in detail either the theory behind the approaches used to extract useful diagnostic information nor the various types of instrumentation used, but will rather identify some examples of effects that can be identified.

In no way is it the intent of this paper to suggest that motor current or power analysis be considered as a replacement diagnostic for technologies such as vibration. There are clearly many defects and conditions detectable through vibration measurements, for example, that are not detectable through the motor data. However, there are some conditions for which motor data is more sensitive than most other diagnostic methods. There are also situations where it is easier to implement than many other techniques. Finally, it can be useful in confirming indications developed from other diagnostic techniques.

Typical motor performance characteristics: The early applications of motor current signature analysis focused on current specifically because of the ability to acquire current data in a relatively non-intrusive fashion (using a clamp-on current transformer, for example), as opposed to the somewhat more intrusive nature of power and power factor measurements which require direct connection to the motor supply leads.

A typical motor performance curve for a 4-pole 150 hp motor is shown in Figure 1. Note that the input power is very linear with output power across the full range of motor load; over the range from 50 to 150 bhp, the current is essentially linear as well. The power factor is relatively insensitive to load variations within this region, particularly near rated load. At very light loads, the current response to load changes is small, while the power factor changes dramatically with relatively small changes in motor load. Motor performance curves do vary somewhat for different designs, but the general performance characteristics are not dramatically different in the normal operating range.

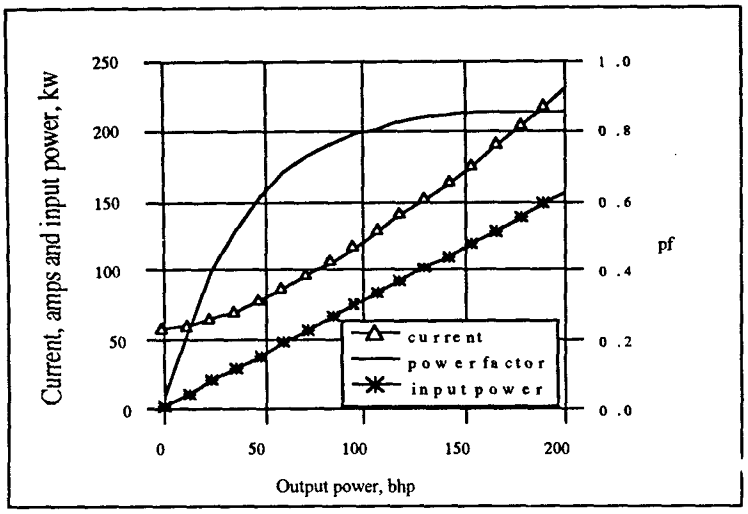


Figure 1. Typical Motor Performance Characteristics

There are complicating factors, such as deviation of actual bus voltage from design and power quality-related issues, that limit the accuracy of generic, or even motor-specific curves. However, a variety of motor models have been developed recently which have been found to be capable of predicting motor output power accurately to within three percent or better [2].

It is important to recognize that motor performance curves such as that shown in Figure 1 are typically based on measurements averaged over periods of seconds or minutes. On an instantaneous basis, significant departure from these average values may occur. For example, the head and flow developed by a pump at low-flow conditions are often less stable than when the pump is operated near its best efficiency point. The instability may consist of both some relatively well-defined frequency components, such as vane-passing as well as more chaotic instabilities that are manifested as broad band noise. When such instabilities affect shaft torque (and as a result, motor load), it becomes possible to detect both the existence and magnitude of the instabilities, at least in a relative context.

To a great extent, vibration monitoring is a useful diagnostic technique because of similar considerations. Accelerometers, for example, do not measure absolute forces for rotating equipment; rather, they sense the acceleration occurring in response to fluctuations in forces. The long history of vibration monitoring has provided a basis for not only rules of thumb, but industry standards.

At this point in time, there is minimal experience in the use of motor-transduced data as a system diagnostic. At ORNL and at the Y-12 defense plant, motor current and power data for a variety of equipment have been collected over the last few years. Motor current or power has been found to provide insights into both the monitored component specifically and to overall system conditions, as well. The balance of this paper will discuss examples of the types of results that have been found.

Comparison of the sensitivity of motor input power and vibration measurements to common sources of vibration: From test data acquired on a variety of types of equipment over several years, fluctuations in motor spectral data that are related to some load component have been observed. In many cases, researchers and test personnel have been content to observe the existence of some load-related peak in the spectral data, and perhaps trend the amplitude with time. It was noted during certain tests that there were characteristic peaks in the motor current or power spectra that also existed in vibration spectra. Motor power and pump vibration spectra for a belt-driven positive displacement vacuum pump are shown in Figures 2 and 3. The loads associated with belt pass, pump stroke, and motor running speed can be clearly seen in the motor power spectrum. Some, but not all of the spectral peaks also appear in the vibration spectrum; the most noticeable difference is the absence of most of the belt pass frequency components from the vibration spectrum. This is typical for belt-driven devices, and is due to the torsional load fluctuations associated with both belt irregularities and belt looseness. While loose belts can result in elevated vibration in the radial direction, the radial effect is not nearly as dramatic as the torsional effect. As a result, radial vibration is often minimal, as was the case for the vacuum pump.

Positive displacement pumps, by their very nature, involve considerable torque fluctuations at the drive shaft during individual compression sequences. These torque fluctuations are readily transduced by the motor; as a result, the spectral amplitudes associated with pump compression frequencies are usually distinct (e.g., Figure 2), and are very sensitive to flow and head changes.

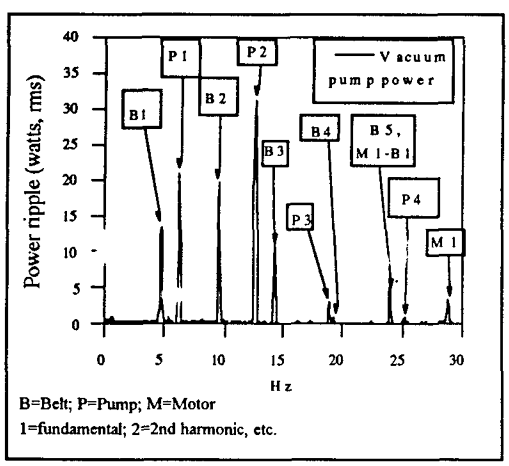


Figure 2. Motor Input Power Spectrum for Belt-Driven Vacuum Pump

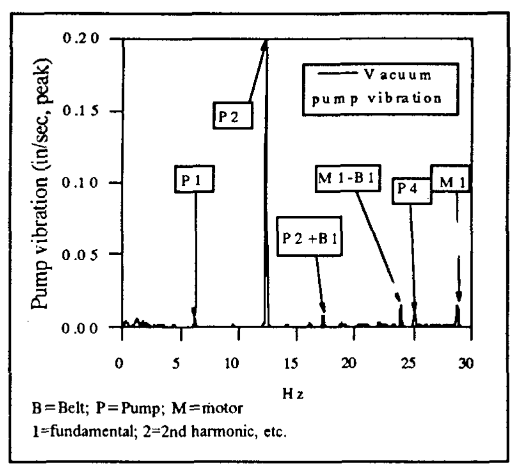


Figure 3. Vacuum Pump Vibration Spectrum

In general, motor-based measurements are more sensitive to torsionally-related loading than radial or axial vibration data. On the other hand, the motor is, generally speaking, a relatively poor transducer of radial and axial vibration that is not accompanied by torsional loading. Fundamentally, in order for a radial or axial load fluctuation to be seen in motor data, the radial or axial load must either result in relative motion between the motor rotor and stator and/or cause a change in torsional load.

Sensitivity to mechanical unbalance: A comparison of the results of vibration and motor data measured during tests conducted to measure the effects of unbalance and alignment have validated the observation that the motor, as a transducer, is primarily sensitive to torsional loads. In a controlled balance test performed at Oak Ridge, measurements of motor input and output data and vibration amplitude were made as the mechanical balance of a motor was changed. For this test, a 4-pole, 50-hp motor was connected to an eddy-current brake dynamometer, and the mechanical balance was changed by using a dynamic balancing device provided by Balance Dynamics, Inc. The dynamic balancer allows for on-line balancing of rotating equipment by moving fluid between chambers in a wheel attached to the shaft. The primary purpose of the test was to determine if mechanical balance had any effect on motor efficiency. While there was marginal, if any, effect on motor efficiency, a relatively well defined correlation was found between radial vibration and motor input power spectra. A plot of the energy of a running speed-related frequency from the motor power spectrum vs. motor inboard horizontal vibration velocity is provided in Figure 4. This almost linear relationship is not necessarily reflective of all types of unbalance. In this particular test, the balance wheel was located between the motor and the coupling. In field testing conducted on a 6000-hp fan motor, where two balancing wheels were used on the inboard and outboard ends of the fan, there was no observable change in motor spectra as the balance was changed. In the case of the 50-hp motor, it is likely that the unbalance forces resulted in slight dynamic changes in rotor to stator air gap, and thus was reflected in the motor data, while for the 6000 hp motor, the unbalance location (on the fan side of the coupling) affected neither the torsional shaft load nor the rotor to stator air gap.

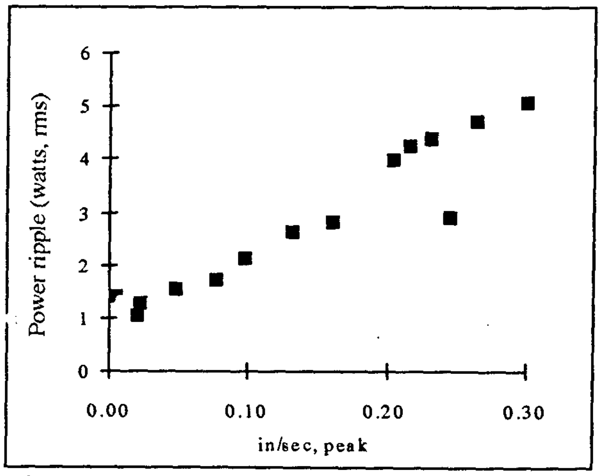


Figure 4. Power Ripple vs. Vibration Amplitude - Running Speed-Related Components for an Unbalanced Rotor

In general, motor data is very insensitive to mechanical unbalance. Note that even for the data shown in Figure 4, only a few watts of energy are involved. The motor was being run at its rated condition of 50 hp (output). The motor input power was about 41000 watts. About 0.01 percent or less of the motor energy was associated with the unbalance. On the other hand, the vibration data was dominated by the mechanical unbalance. Thus, although mechanical unbalance may be

detectable from careful analysis of motor data, it is neither a reliable nor sensitive indicator of unbalance, particularly when the unbalance exists on the driven device side of the coupling.

Sensitivity to misalignment: Because misalignment fundamentally results in not only radial and axial vibration, but torsional loading, the motor has been found to be a very sensitive transducer of misalignment. Testing at the Y-12 plant is presently assessing the effects of alignment on motor system efficiency. In conjunction with this testing, the sensitivity of motor and vibration data to alignment changes are being evaluated.

Motor inboard vibration, output torque, and input power spectral data for a 10 hp, 4-pole motor after laser alignment to the dynamometer are shown in Figures 5-7. Spectra for the same parameters with the motor outboard feet elevated by 20 and 30 mils are shown in Figures 8-10 and 11-13, respectively.

The running speed and two times running speed motor power (input) ripple and vibration velocity vs. output torque ripple for these and several other misalignment conditions are shown in Figure 14 and 15. Note that the amplitude of vibration is very low, even for the most severely misaligned condition (motor inboard feet elevated by 40 mils).

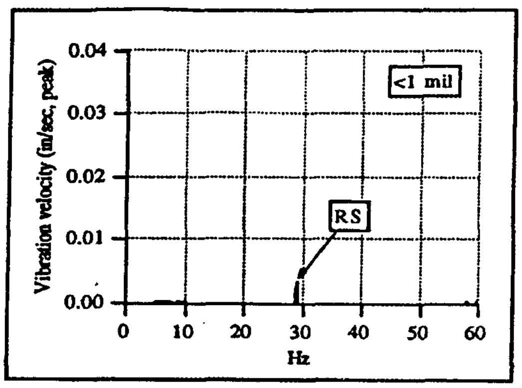


Figure 5. Well-Aligned Vibration Spectrum

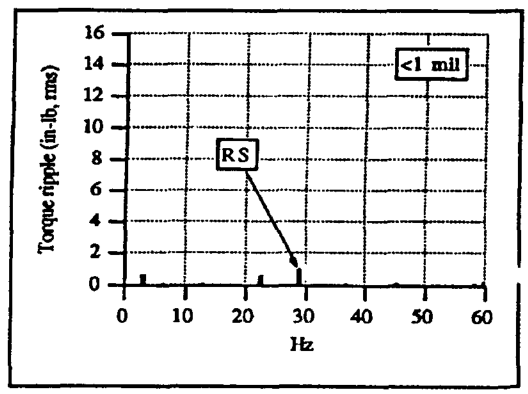


Figure 6. Well-Aligned Torque Ripple Spectrum

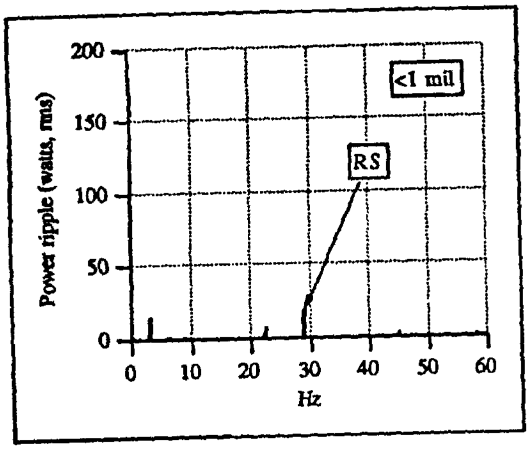


Figure 7. Well-Aligned Power Ripple Spectrum

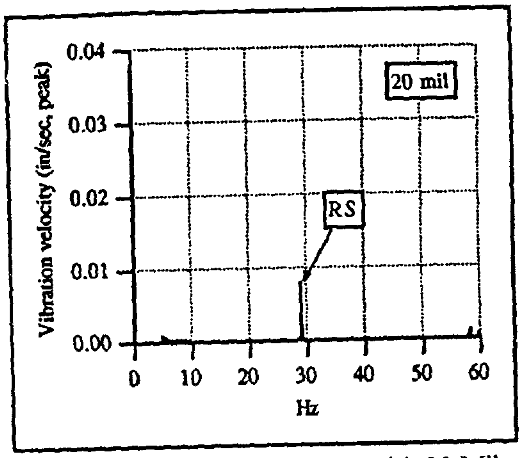


Figure 8 Vibration Spectrum with 20 Mil Shim

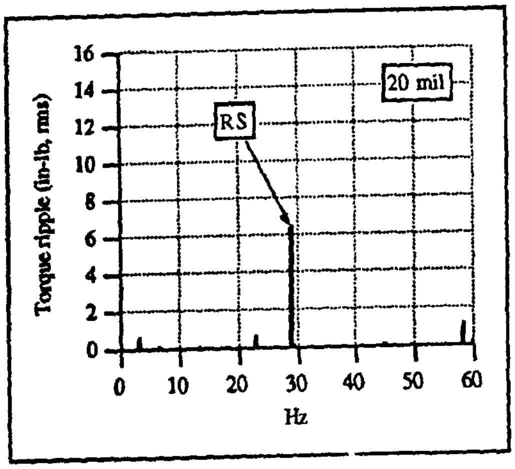


Figure 9. Torque Ripple Spectrum with 20 Mil Shim

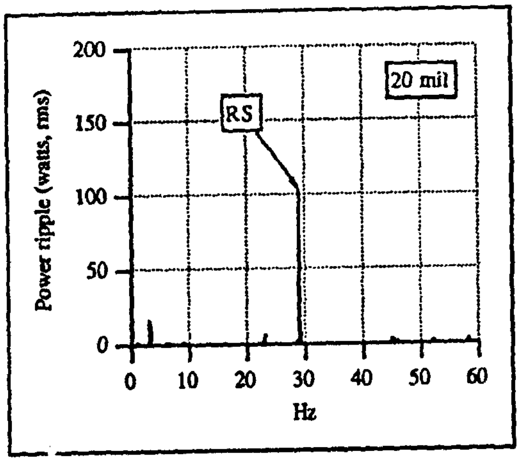


Figure 10. Power Ripple Spectrum with 20 Mil Shim

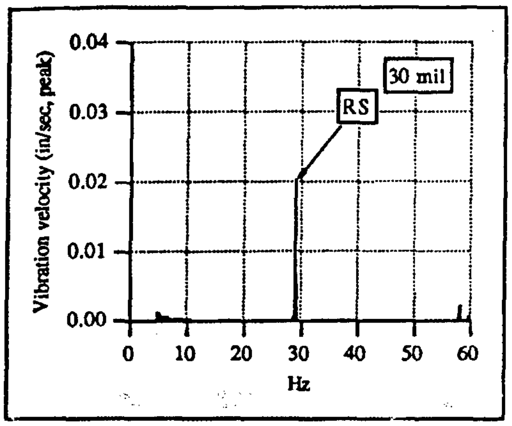


Figure 11. Vibration Spectrum with 30 Mil Shim

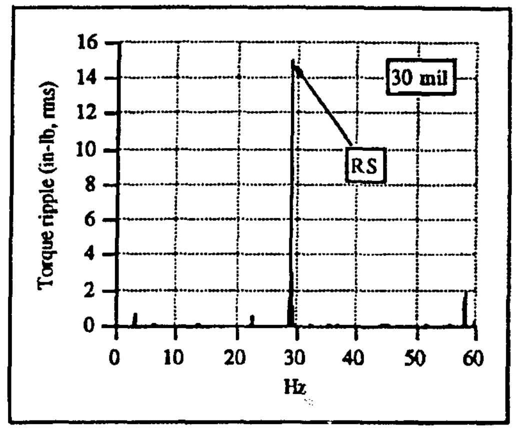
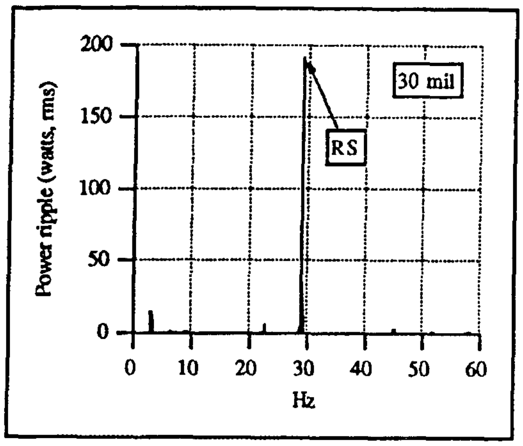


Figure 12. Torque Ripple Spectrum with 30 Mil Shim



Figur ˙3. Power Ripple Spectrum with 30 Mil Shim

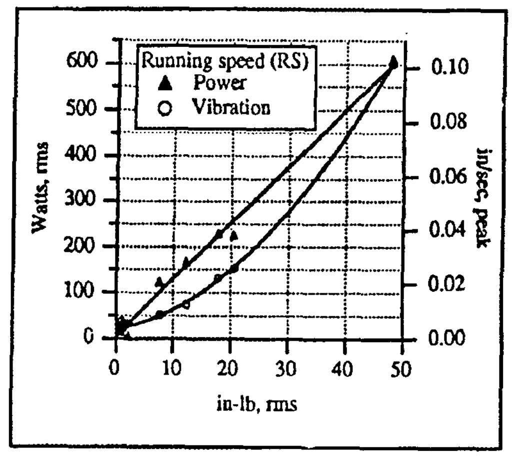


Figure 14. Running Speed Pow... Ripple and Vibration vs. Torque Ripple at Various Levels of Misalignment

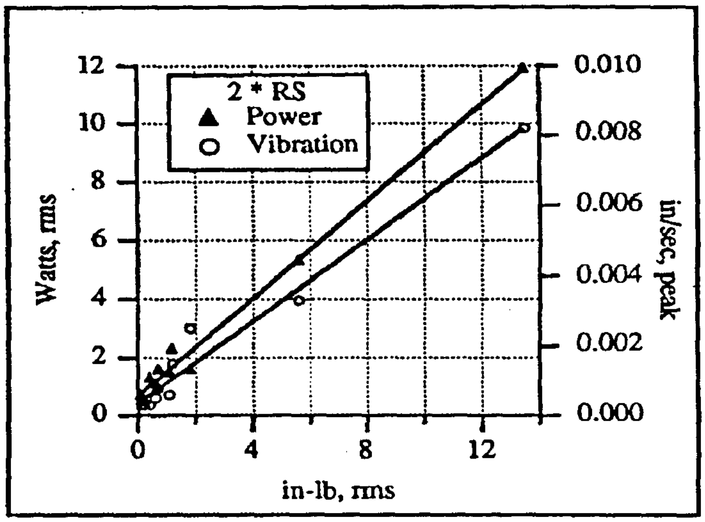


Figure 15. Two Times Running Speed Power Ripple and Vibration vs. Torque Ripple at Various Levels of Misalignment

Results of on-line monitoring: The Y-12 plant is in the process of implementing on-line motor current monitoring for motors used in a variety of processes. Both overall amplitude and spectral data are periodically acquired and logged. The data are archived and trended in the same database used for periodic vibration monitoring.

This system is still not fully implemented, but it has proven useful in detecting degraded component conditions. Two examples are provided below which are illustrative of both the capability and limitations of motor current/power monitoring.

Clogged suction strainer: Motor current for several pumps used in a chilled water facility are periodically monitored. A trend plot of motor current for two identical pumps operating in parallel over the course of 35 days is shown in Figure 16. In Figure 17, the motor power spectrum for the J102 pump at the end of the trend period is shown. Power spectral data for the same pump with a clear suction strainer is shown in Figure 18. From the combination of overall current trend and spectral data, as well as knowledge of previous experience for these pumps, it was deduced that the J102 pump suction strainer had become clogged. Subsequent removal of the suction strainer showed considerable clogging (Figure 19). Vibration data acquired for these pumps (not shown) failed to indicate significant differences.

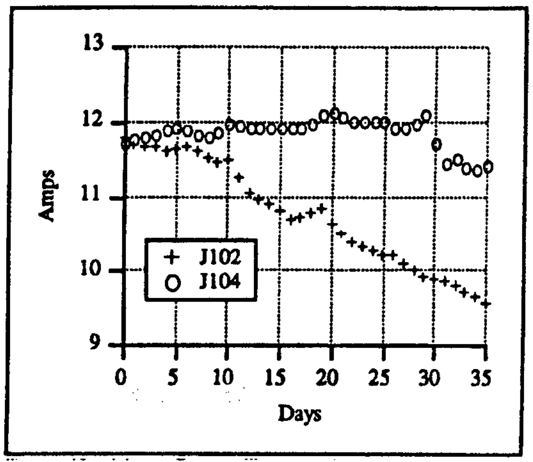


Figure 16. Motor Current Trend for Parallel Pumps

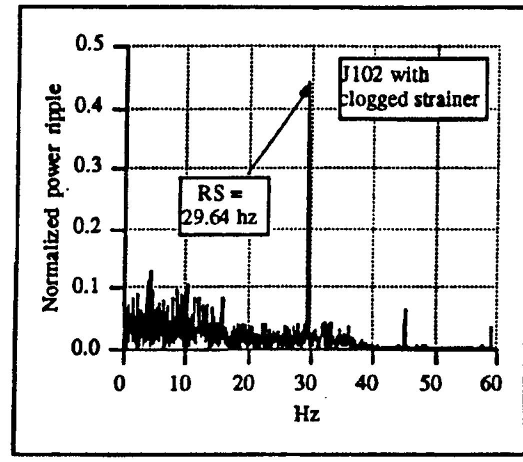


Figure 17. Motor Power Spectrum for Pump with Clogged Suction Strainer

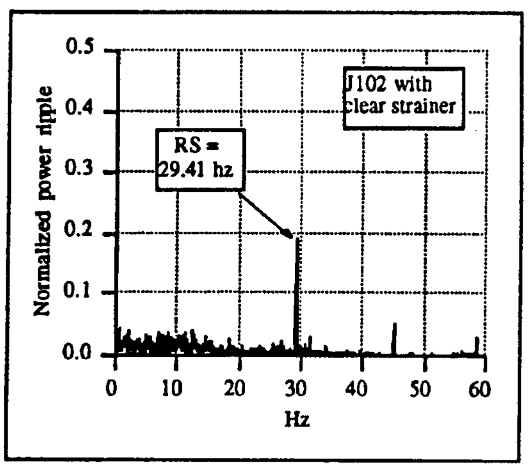


Figure 18. Motor Power Spectrum for Pump with Clean Suction Strainer

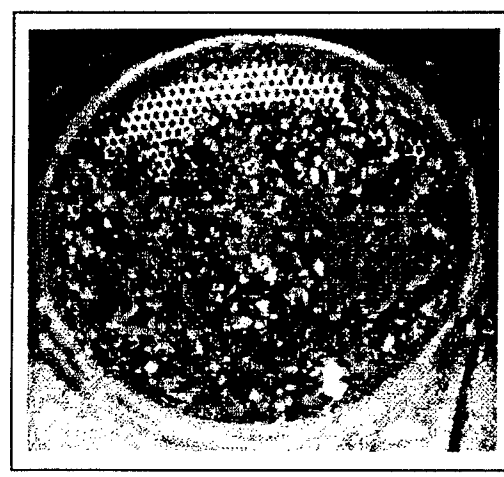


Figure 19. Clogged Suction Strainer

Damaged motor bearing: Spectral vibration data from a belt driven exhaust fan motor indicated the presence of a severe bearing defect (Figure 20). Since this motor had been recently put on the on-line current monitoring system, the motor current spectrum was evaluated for confirmatory indication. As shown in Figure 21, the fault frequency was also seen in the current spectrum. The amplitude shown for the current spectrum in this case is relative amplitude. Note that the fault here was in a motor bearing, and it was severe; even then, the amplitude of the fault frequency in the motor data was extremely small. There have been no examples at the Oak Ridge facilities where bearing faults in the driven equipment have been detected by motor spectral data. Also, many cases have been found where less severe motor bearing flaws have been detected by vibration data with no corresponding indication in the motor spectral data. Two important conclusions from the vibration and current data analysis experience relative to bearing fault

detection can be drawn:

- Spectral vibration data is much more sensitive to bearing fault conditions than motor data.
- Although severely degraded motor bearing faults may be manifest in the motor spectral data, it is judged to be unlikely that anything less than a severe fault would result in detectable levels in the current or power spectrum. Degradation in driven device bearings would be even less likely to be sensed by motor current or power spectral data.

These observations relative to bearing degradation are not based on controlled research studies, but rather on observations from field data. They are certainly not conclusive, but represent experience from a variety of motors and driven equipment.

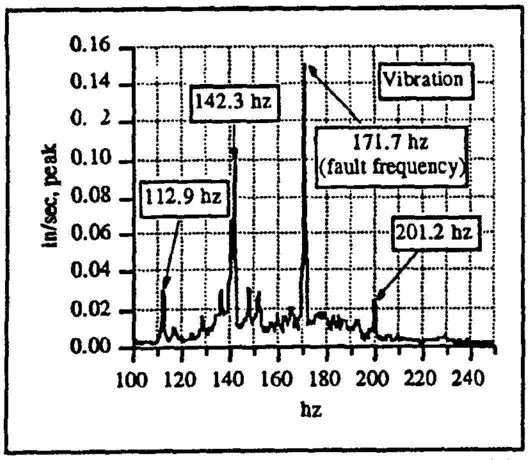


Figure 20. Vibration Spectrum for Motor with Damaged Bearing

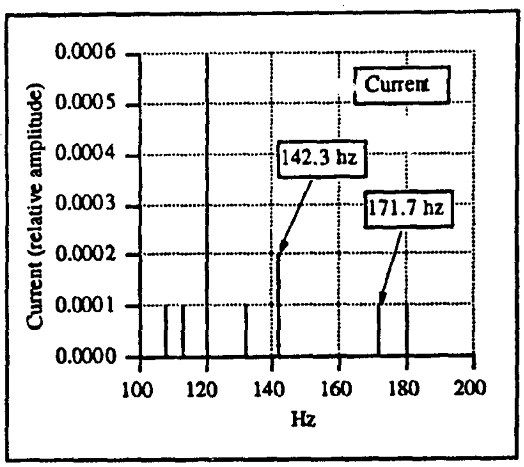


Figure 21. Motor Current Spectrum for Motor with Damaged Bearing

Resources: The use of motor current or power data in analyzing load behavior is not a well-developed field. For those that are interested in exploring its potential, the following may be of interest:

- The technologies developed at ORNL and at Y-12 to assess equipment performance from motor data have been licensed by several domestic diagnostic service companies, including ITI MOVATS, Inc. (a Westinghouse company), and Babcock and Wilcox, Inc. These organizations provide both diagnostic systems and field service based on the motor-monitoring technologies.

- ORNL and the Y-12 plant, both of which are Department of Energy facilities, have ongoing motor-related activities in both the research and facility operation support arenas. Motor data from pumps and other equipment are being used and analyzed in a variety of ways to improve operational efficiency and reliability, minimize unplanned maintenance, and reduce operational costs, as well as to support research objectives. Inquiries about technical aspects of these activities may be addressed to the authors.

Conclusion: Monitoring important system performance parameters by using the motor as a transducer has been found to be both feasible and cost effective. Fundamentally, the motor is effective at transducing torsionally-related load phenomena.

The motor can be effectively used as a transducer to aid the understanding of both alignment and process conditions. In contrast, the motor has not been found to be a particularly effective transducer of mechanical unbalance or bearing fault conditions.

Motor current and power analysis offer an alternative diagnostic approach that may be used in conjunction with existing diagnostics, or in some cases, as a primary diagnostic. As more experience is gained in its field use, it is expected that it may become possible to establish experientially-based indications of the acceptability of certain characteristic loads, such as those associated with misalignment or overall load stability.

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